



Summer hypoxia adjacent to the Changjiang Estuary

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Abstract

Changjiang, the third largest runoff in the world, empties into the East China Sea from Shanghai, the fastest developing area of China. With the increasing nutrient load from the river, a severe hypoxia zone was found to about $2 \times 10^4 \text{ km}^2$. The mechanism of hypoxia formation adjacent to the Changjiang Estuary receives more and more attention from both scientists and managers. This paper discusses the relationship between hypoxia and the water masses, primary production, particulate material transport and the density stratification in these areas according to data obtained from a cruise in September, 2003. Hypoxia is formed by organic detritus decay. The particulate organisms do not mainly come from the Changjiang river, or from the dead algal deposited locally, but from the local benthic algae or particles advected from the south. Maintenance of hypoxia is due to the large density stratification caused by the significant salinity difference between the fresh plume and salty water from Taiwan Strait. This applies also to other estuaries with large runoff and rapid economic growth drainage, such as the Pearl River. It is suggested that the hypoxic zone here is much more sensitive than that outside Mississippi River. More cruises over different weather and tide conditions are needed to prove this hypothesis. Interdisciplinary research should be further developed in the future.

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Keywords: Hypoxia zone; Organic detritus decay; Density stratification; Nutrient load; Fresh water plume; Changjiang estuary

1. Introduction

Hypoxia is defined as dissolved oxygen (DO) concentration less than 2 mg l^{-1} —the level at which bottom trawls fail to capture fish, shrimp or crabs (Renaud, 1986). There has been much attention paid to presumed anthropogenically induced hypoxia in shallow and enclosed seas; areas of eutrophication generated hypoxia occur in the Gulf of Mexico (up to $20,000 \text{ km}^2$), Baltic Sea ($84,000 \text{ km}^2$) and parts of the Black Sea ($<20,000 \text{ km}^2$) (Rabalais and Turner, 2001; Mee, 2001). Many other river-dominated estuaries like Chesapeake

Bay, Adriatic Sea, German Bight and the southern North Sea also suffered hypoxia and noxious phytoplankton blooms (Justic et al., 2002). The current understanding about the causes of hypoxia is that riverine nutrient loading, principally as nitrate-N, increased in the last half of the 20th century and stimulated in situ production of organic material which, when it sinks to the bottom layer, consumes oxygen faster than it can be replaced by vertical mixing through a stratified water column. It is believed that the nutrient loading by the discharge, via exacerbating the increase of net productivity, plays a major role in the development of bottom water hypoxia. Turner et al. (2005) established a polynomial regression formula to predict the hypoxic zone size from total Kjeldahl nitrogen at the shallow water stations on the

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shelf of Louisiana, which are mainly input by the Mississippi River. The multi-agency and collaborative Action Plan adopted for the watershed is intended to reduce the size of the hypoxic zone to 5,000 km² (5-year running average) by 2015, by reducing the overall riverine nitrogen load by 30% (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2001). Justic et al. (2003) point out that the hypoxia formation is more complicated as it is influenced by climate and other physical processes (in addition to river nutrient load increasing) so that a 30% decrease in the nitrogen flux of the Mississippi River may not be sufficient to accomplish the proposed hypoxia management goal.

The minimum DO concentration adjacent to the Changjiang estuary has been documented since 1959 (Gu, 1980). Summer hypoxia appeared in this area in the early 1980s (Limeburner et al., 1983) and became severe in recent decades (Tian et al., 1993; Li et al., 2002). The center of the hypoxic area is around 123°E, 31°N which was outside the coastal front. The nutrient input from the Changjiang drainage doubled in the past two decades. Harmful algal blooms frequently broke out in this area (Zhang et al., 1999). The mechanism for hypoxia formation adjacent to the Changjiang Estuary receives more and more attention from both scientists and managers. What is the control condition for the extension and duration of hypoxia in this area? How can we reduce the influence of frequently harmful algal blooms (HAB) and hypoxic volume? Other studies have dealt with these problems. This paper only discusses the relationship between hypoxia and the water masses, primary production, particulate material transport and the density stratification in these areas using data

obtained from a cruise in September, 2003, which was carried out by the Chinese GLOBEC (Global Ocean Ecosystem Dynamics) and a key international cooperation project (Hydro-geochemistry processes and their environmental effect induced by discharge in coastal sea of China, 2001CB711004) both funded by the Ministry of Science and Technology of China.

2. Stations and measurements

From September 4–25, 2003, we carried out a cruise in a fan-shaped area adjacent to the Changjiang Estuary (Fig. 1) on board DongFangHong 2 R/V. There were 6 sections from the northern corner of the Changjiang mouth (Section Y with stations Y5–Y1) to the south around Zhoushan Islands, including PN section with stations P12–P3. Stations with depths of less than 100 m were mainly for the research of hypoxia. Four stations in the estuary (CHJ1–CHJ4) were added to check the character of diluted water with lowest salinity of 2. From 5 m to 100 m isobaths the topography varies slowly and extends to about 400 km at the widest part.

A SeaBird 911⁺ CTD with Seapoint sensors of Chl-a and turbidity was downcast at 34 stations. The dissolved oxygen concentration profile was measured by a YSI 6600 sensor at the same stations and water samples were obtained by a Niskin sampler rosette. Measurement of DO was done at 3–5 layers at each station on board by the biogeochemistry group in order to calibrate DO data taken by the YSI 6600 sensor. Current profiles were obtained by two ship-mounted ADCPs, 75 kHz and 350 kHz, respectively. The temperature, salinity, Chl-a and turbidity data obtained by the SeaBird 911⁺ was

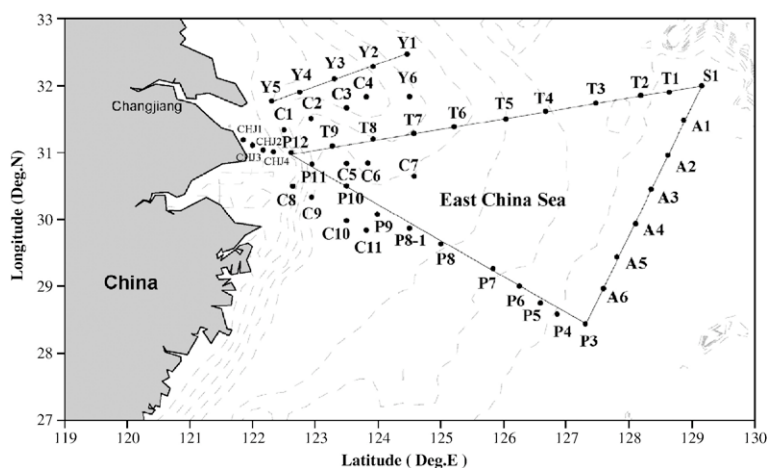


Fig. 1. September, 2003 cruise stations and the topography of the East China Sea.

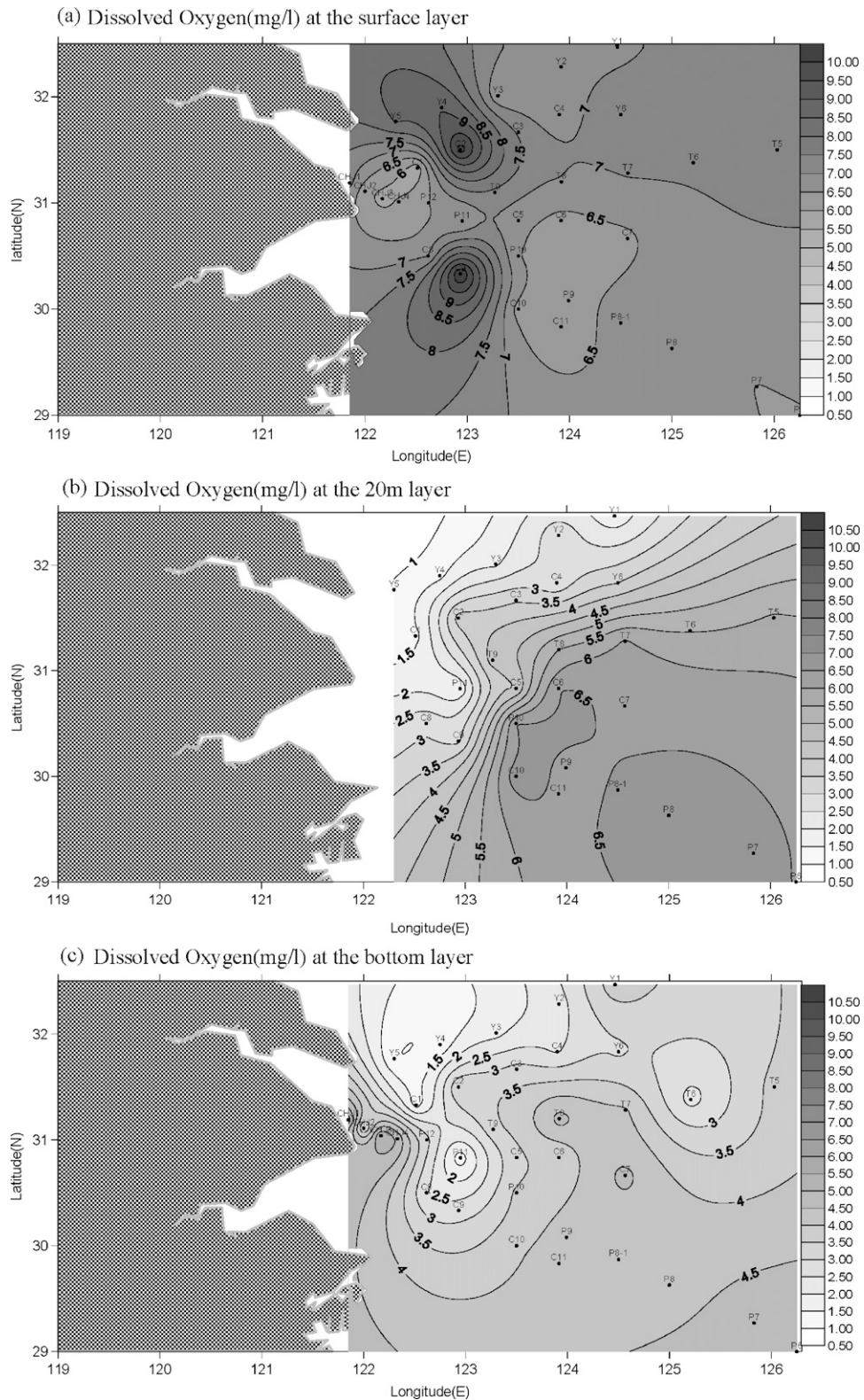


Fig. 2. Dissolved oxygen concentration distribution at (a) the surface (b) 20 m and (c) the bottom layer.

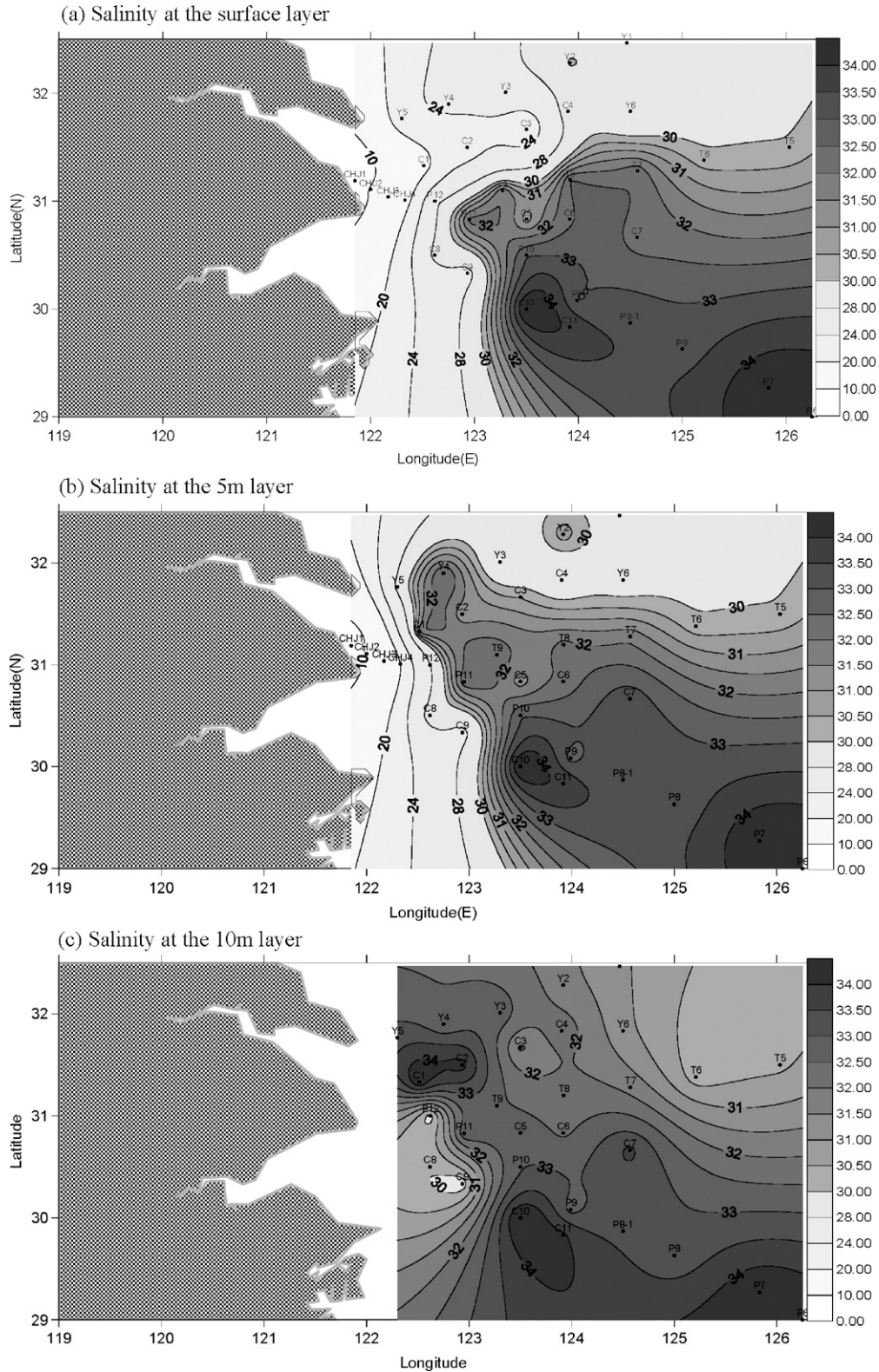


Fig. 3. Salinity distribution at (a) the surface (b) 5 m (c) 10 m (d) 15 m (e) 20 m and (f) the bottom layer.

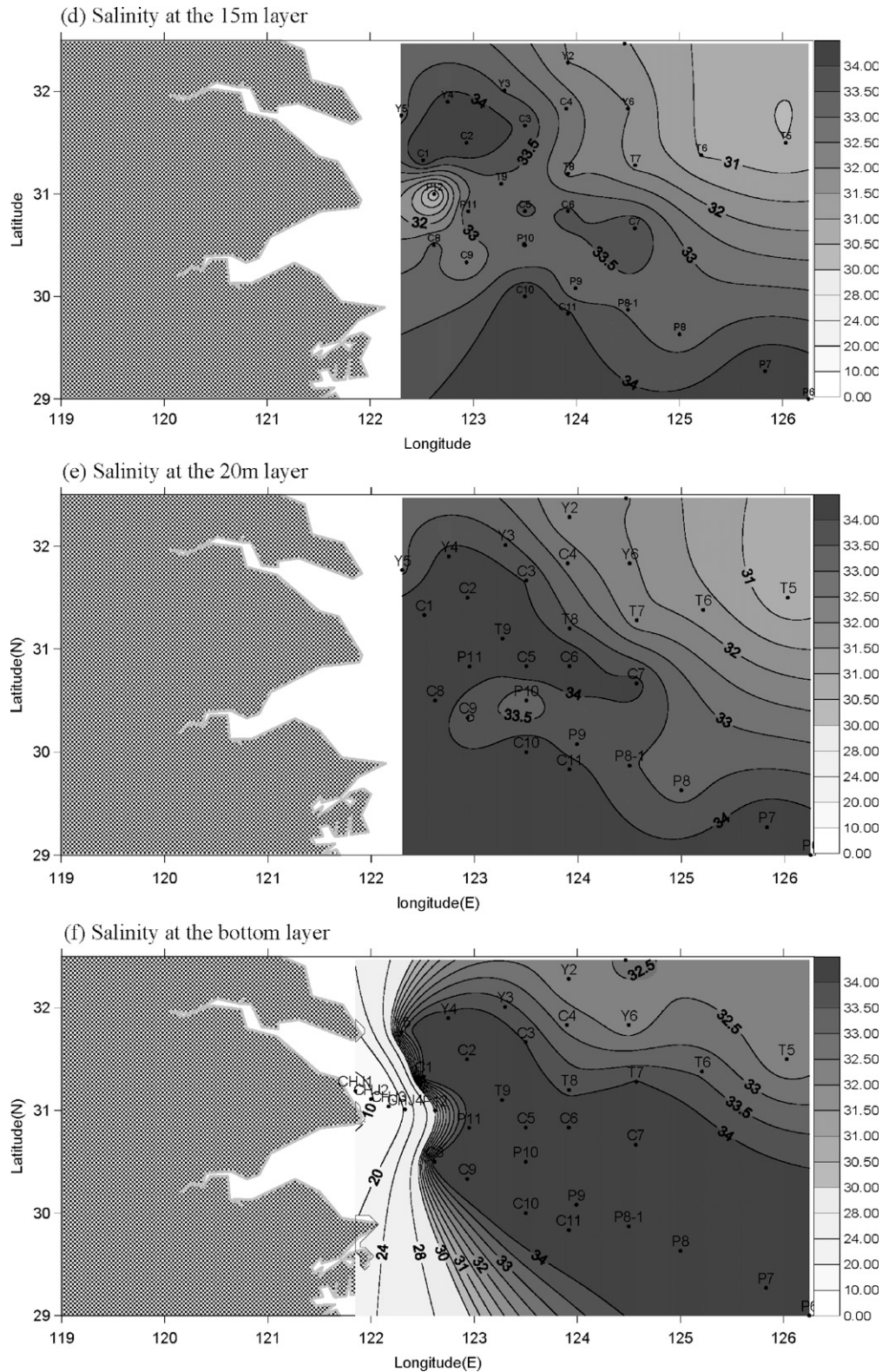


Fig. 3 (continued).

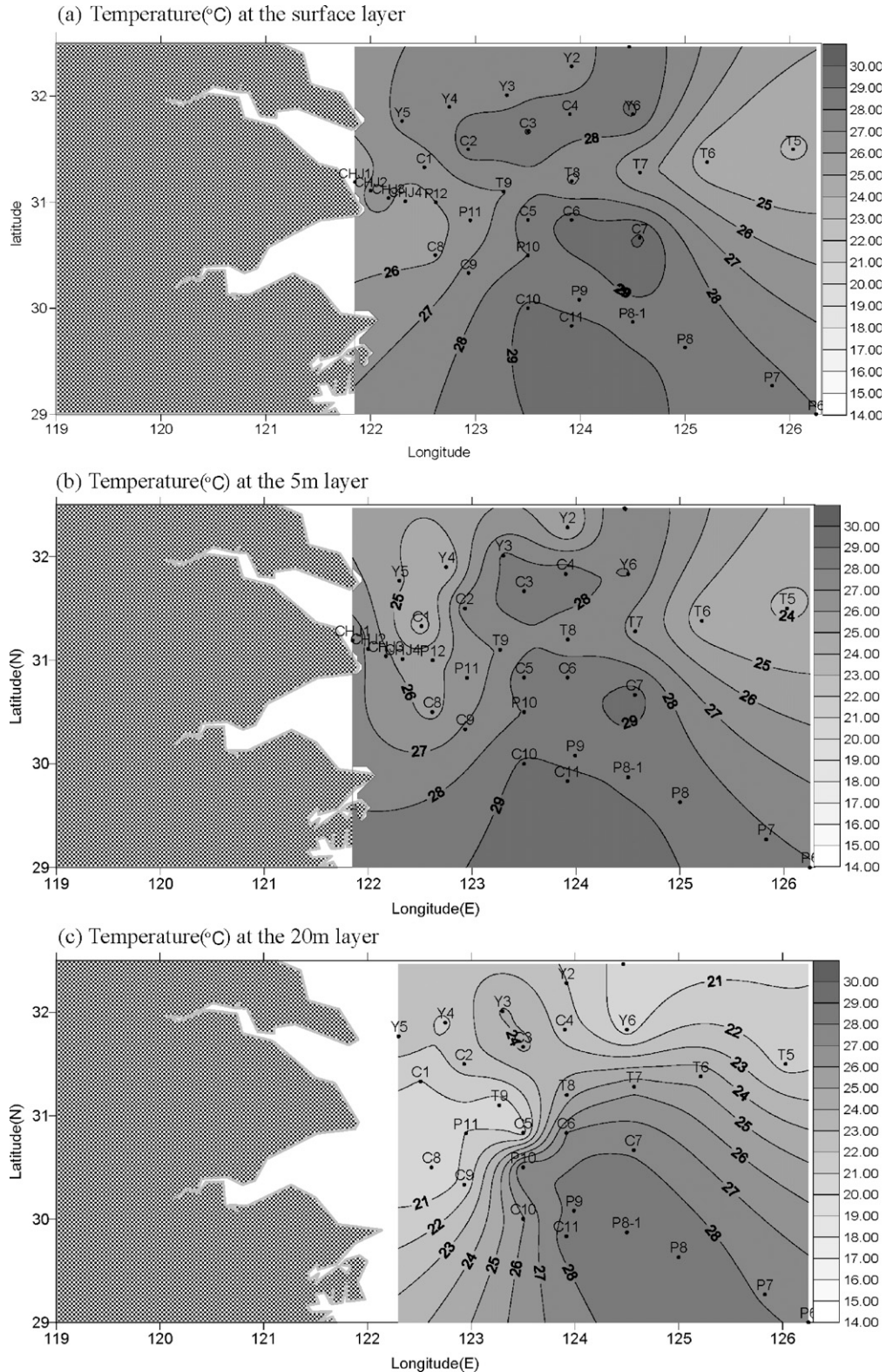


Fig. 4. Temperature distribution at (a) the surface (b) 5 m (c) 20 m and (d) the bottom layer.

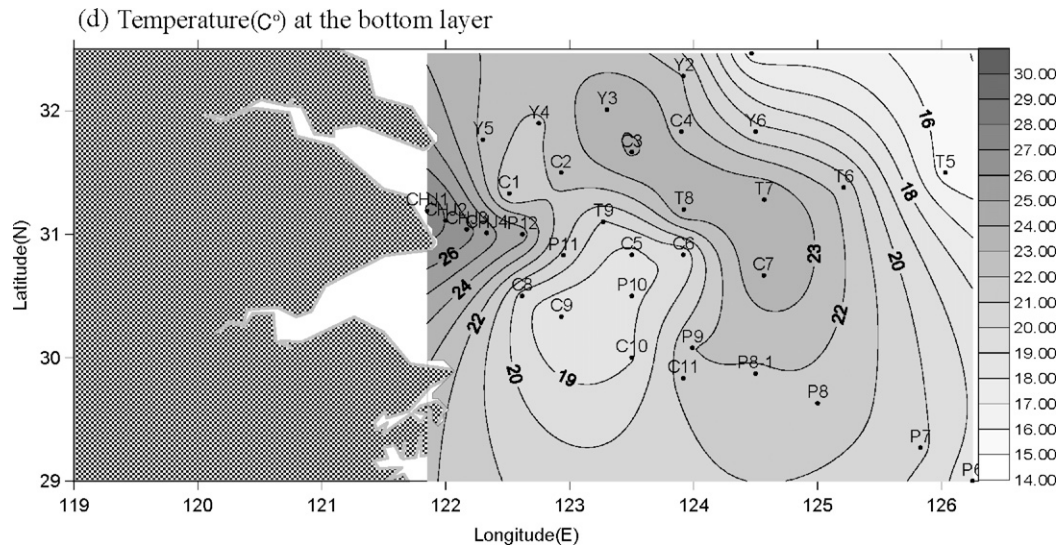


Fig. 4 (continued).

filtered and averaged at 0.5 m intervals. The response time of the YSI 6600 DO sensor is very slow and the sample time interval was set to 8 s. The YSI sensor was put down separately with the CTD at a lower speed to obtain 2 or 3 measurements in a 1 m interval.

3. Analysis and discussion

3.1. DO distribution adjacent to the Changjiang Estuary

DO of stations CHJ1–CHJ4 was about $5 \text{ mg} \cdot \text{l}^{-1}$ from the surface to the bottom. This area was well mixed since the depth is only about 5 m. Salinity was less than 10. The colder fresh water from the Changjiang river has sufficient dissolved oxygen for organisms to survive. DO in the surface layer was $6\text{--}10 \text{ mg} \cdot \text{l}^{-1}$ and two patches of high DO were found at station C2 in the north and at station C9 around the Zhoushan Islands in the south (Fig. 2a). Hypoxia first took place at the 5 m layer of station C1 and then extended to the north-east in deeper layers. At the 20 m layer DO of stations in the middle shelf was larger than $6 \text{ mg} \cdot \text{l}^{-1}$, while in the inner shelf was less than $4 \text{ mg} \cdot \text{l}^{-1}$ (Fig. 2b). From the bottom distribution we can see that there was a north–south band of hypoxia outside the coastal mixing area (Fig. 2c). The lowest DO was $0.8 \text{ mg} \cdot \text{l}^{-1}$ at station P11 ($122^{\circ}56'\text{E}$, $30^{\circ}49'\text{N}$). However the area of hypoxia in the north was much wider which could extend to the whole section. The $3 \text{ mg} \cdot \text{l}^{-1}$ DO contour has the same curvature with 50 m isobaths in the north. The hypoxic zone was estimated to be $2 \times 10^4 \text{ km}^2$ along the isobaths of 20–50 m.

3.2. Water masses in the investigated area

Salinity varied from 2 to larger than 34.5. The axis of the fresh tongue is along section C (stations C1–C4 and Y6) (Fig. 3a). The fresh water runs northeastward first out of the river mouth in summer due to the southerly monsoon. The inner shelf was full with fresh water (salinity < 30) in the upper 5 m (Fig. 3b). Diluted water from Hangzhou Bay can be identified at C8, C9 stations from 10–15 m depth salinity distribution (Fig. 3c and d). It is quite different at the 20 m layer, where less salty water occupied the middle shelf outside the inner shelf and the most salty water was found at stations C1, C2 and C6, just outside the Changjiang Estuary (Fig. 3e). A fresher layer (salinity < 31) could be seen pointing from the north-east corner to the south-west between 10–20 m. High salinity water (salinity > 34) intruded to the inner shelf from south-eastward and followed close to the coast when it met with the fresher water from north-east at 20 m depth under the diluted water from Hangzhou Bay and upwelled to the 10 m at stations C1 and C2. 34 salinity contours could get 32°N , north of Changjiang Estuary, at the bottom layer (Fig. 3f). A 2°C difference was found for the sea surface temperature with slightly cool water near the Changjiang mouth and at the north-east corner (Fig. 4a). Two cold centers appeared at 5 m depth at stations C1 and T5, the former was consistent with the high salinity indicated the upwelling (Fig. 4b). The low DO bottom water upwelled to 5 m at station C1 (Fig. 2b). Warm salty water intruded from the middle shelf in the upper 20 m north-westward to the inner shelf (Fig. 4c). At the bottom, water with the same salinity has different temperature. The temperature was 4°C lower in the inner shelf than that outside

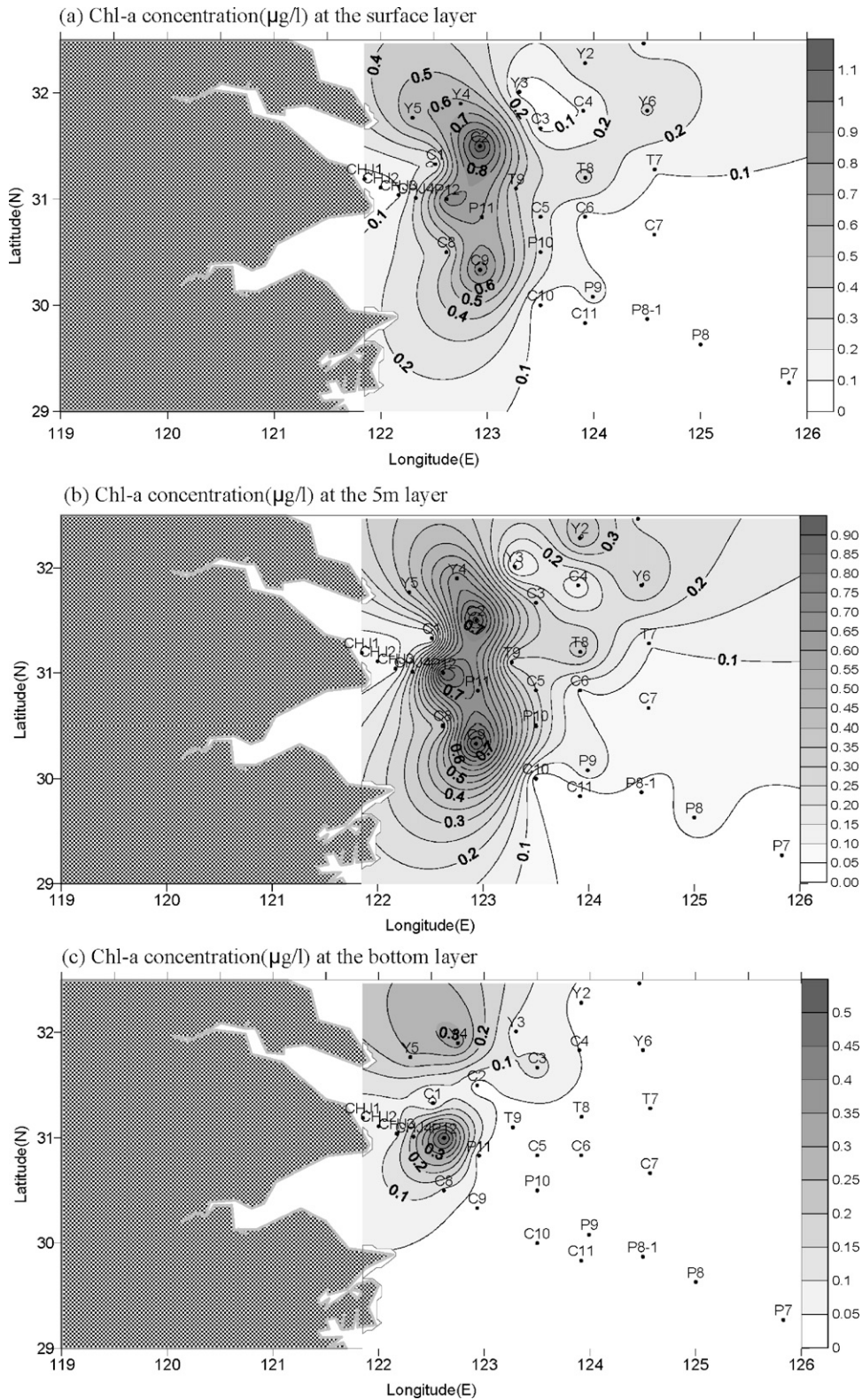


Fig. 5. Chl-a concentration distribution at (a) the surface (b) 5 m and (c) the bottom layer.

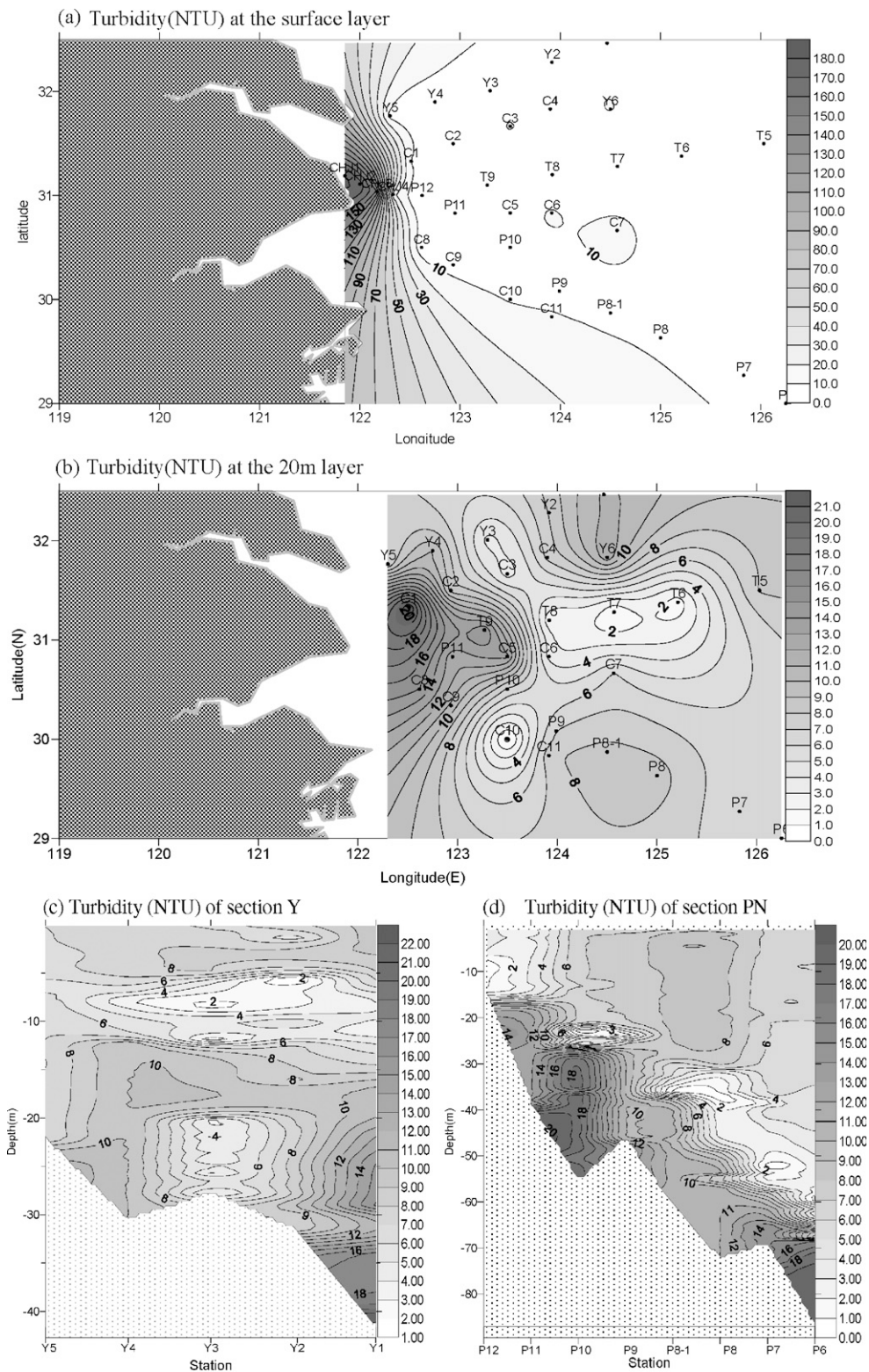


Fig. 6. Turbidity distribution at (a) the surface (b) 20 m (c) section Y and (d) section PN.

(Fig. 4d). It was reported that the current from the Taiwan Strait was bifurcated, with one branch of lower temperature on the inner shelf (Taiwan Coastal Water, TCW) and another branch of higher temperature on the middle shelf (Taiwan Warm Current, TWC).

The water masses in the fan area in September 2003 were Changjiang Diluted Water (CDW) ($S < 30$, $T < 25$ °C) in the top 5 m layer, less salty and cool Yellow Sea Coastal Water ($S < 32$, $T < 25$ °C) flowing from the north-east corner to the inner shelf at the depth of 10–20 m, TCW run northerly with lower temperature ($S > 34$, $T < 19$ °C) from Taiwan Strait on the inner shelf, TWC ($S > 34$, $T > 22$ °C) flowed northerly on the middle shelf, crossing the Changjiang Mouth at the bottom and Coastal Water of the East China Sea. It was obvious that hypoxia is not the character of one of these water masses.

3.3. Chl-a and turbidity distribution in the investigated area

The Chl-a distribution has a close relationship to the high DO value in the top 5 m. There was also a surface high Chl-a band with the center at stations C2, C9 and a lower value patch near stations C3, C4 and Y3 (Fig. 5a). The high Chl-a ($> 1 \mu\text{g}\cdot\text{l}^{-1}$) at station C9, around the Zhoushan Islands, could sustain to 10 m depth, while at C2 less than 5 m. There was a subsurface maximum value of the vertical distribution at station P11, C3 and Y3 (Fig. 5b). Two high Chl-a centers shifted from stations C2, C9 in the surface to stations Y4 and P12 in the bottom layer (Fig. 5c). Chl-a of stations Y4 and P12 reached to $0.25 \mu\text{g}\cdot\text{l}^{-1}$ at the bottom, much higher than that of 20 m depth in the water column. The bottom hypoxia zone was the same as the high bottom Chl-a distribution. The bottom algal, rather than the surface bloom should be the source of the particular organisms which consume the dissolved oxygen when they decay.

The CDW is the most turbid water with turbidity of 180NTU at surface and 1400NTU at the bottom (Fig. 6a). A very sharp turbidity front appeared near the 20 m isobath which was not consistent with the fresh water plume. Outside the front, the water was very clear ($\text{turb}_{\text{surface}} < 10\text{NTU}$, $\text{turb}_{\text{bottom}} < 30\text{NTU}$). The turbidity of station P12, where the surface front of fresh and salty water existed, greatly changed. It was 80–120NTU as measured by an anchored station here in September, 2002, before the Three Gorges Dam was constructed. In the anchored station of this cruise, just 3 months after the dam was finished, it was only 10–30NTU. Most particulate materials transported from Changjiang and Hangzhou Bay settled down within the front. There will be less and less sand input from Changjiang. A high Chl-a band was

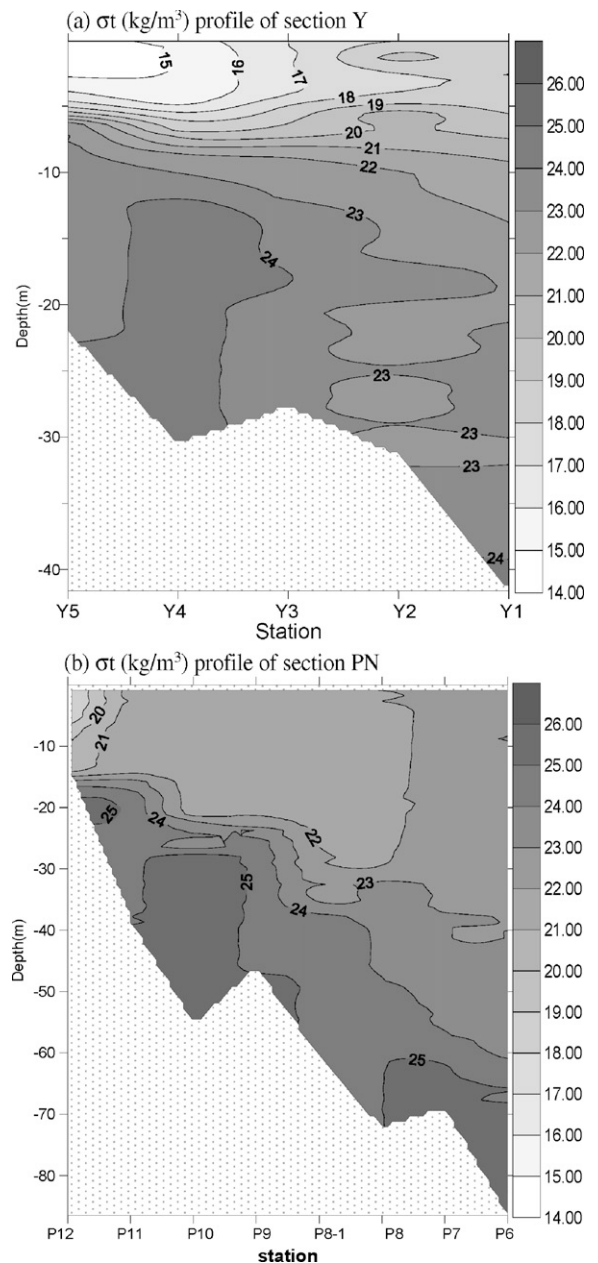


Fig. 7. Density distribution at Y section (a) and PN section (b).

just outside the turbidity front where enough light and nutrients can be obtained for algal growth.

It seems that turbidity is a defining character of the water mass. At 10–20 m the water intruded from the Yellow Sea has the lowest turbidity ($\text{turb} < 4\text{NTU}$) (Fig. 6b). TWC was also clear ($\text{turb} < 4\text{NTU}$), while TCW's turbidity was a little bit higher ($\text{turb} < 19\text{NTU}$) (Fig. 6c and d). The turbidity of section Y shows evidence of the TWC at the lower 10 m of station Y3 and the TCW at the lower 20 m of station Y1 (Fig. 6c). There was no maximum turbidity at

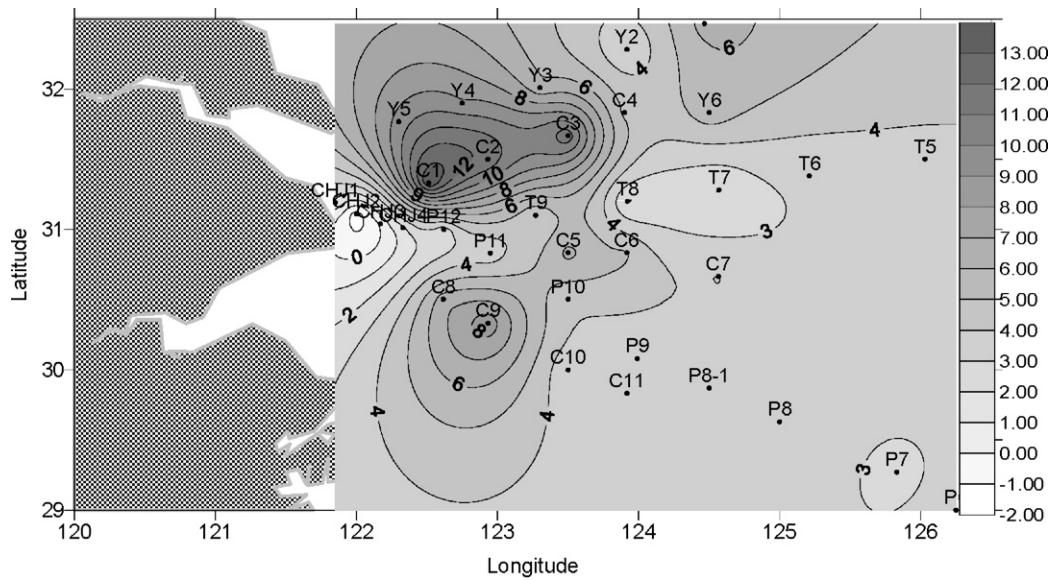


Fig. 8. Density difference between the bottom and the surface.

the bottom due to normal resuspension. The most interesting phenomenon was the minimum turbidity layer ($\text{turb} < 2\text{NTU}$) at the subsurface. This suggests that the particulate materials could not deposit directly from the surface system to bottom system. The two systems were separated and the bottom particles should be mainly advected by the current with water masses. That means high phytoplankton biomass or HAB in the south, around the Zhoushan Islands, could induce the hypoxia in the north sometime afterwards since the dead algae could be transported northerly. Zhu (2004) also showed some evidence of this. Changjiang diluted water should not mainly response for the particulate material input but for the nutrient loads as the base of algal growth.

3.4. Pycnocline and the maintenance of hypoxia

Why were the surface and bottom systems separated? The density distribution and pycnocline are analysed in detail. It is found that the minimum in turbidity took place within the pycnocline (Fig. 7a and b). The pycnocline at section Y was at the depth of 5 m with 5 m thickness and dominated by a salinity gradient. At section PN the pycnocline was stair-like within 5–10 m thickness, as same as temperature distribution. The density difference between the bottom and the surface has the same pattern as the hypoxia zone (Fig. 8). The largest difference was about 12 kg m^{-3} because of the salinity difference between the fresh plume and the bottom salty water from Taiwan. The strong pycnocline could weaken the mixing of dissolved oxygen from the surface layer, where

saturation is reached due to the exchange with the atmosphere and algal growth. Maintenance of hypoxia in such an open area is mainly the result of density stratification. The hypoxic extent and duration are controlled by factors which influence the intensity of pycnocline. During the flood season or in a wet year, the runoff is larger than usual. Hypoxia should develop to far

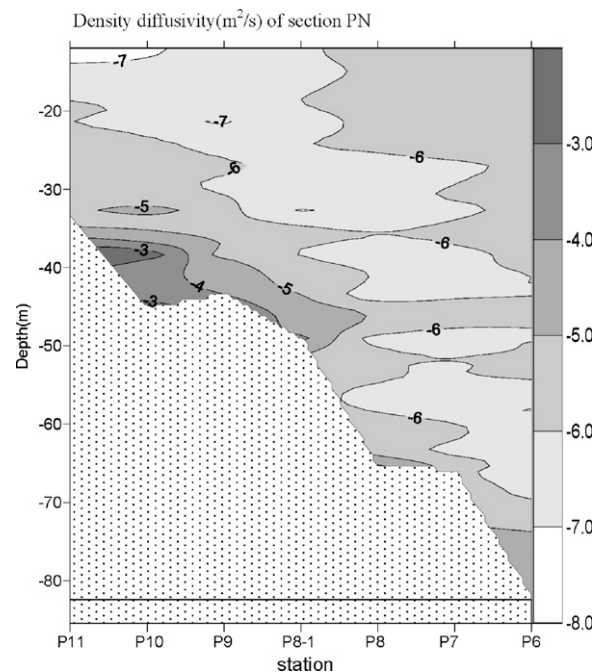


Fig. 9. Density diffusivity at section PN.

distances from the river mouth. With the onset of the north wind, the hypoxic zone disappears quickly since the plume will run south close to the coast and the salty water cannot intrude to this latitude before it turns to the east. It was found that there would be no hypoxia 3 days after the onset of the north wind in our former cruise (September, 2002, unpublished data of our lab).

The density diffusivity (k_p) was simply deduced from the density profiles according to the method of Osborne (1980). k_p of section PN is 2 to 3 orders less in the pycnocline than in the mixing layers (Fig. 9). This could explain why particles and gas of the upper layer did not mix with the lower layer.

4. Conclusion

There exists a large north–south band, much wider in the north, of hypoxia adjacent to the Changjiang estuary. The formation and maintenance of hypoxia is due to the anthropogenically nutrient load through the river and the strong density stratification in the plume. This applies to other estuaries with large runoff and drainage from rapid economic development such as the Pearl River. Since the Changjiang River is in the area of the East Asia Monsoon, the hypoxic zone here is much more sensitive than that outside the Mississippi River. It varies with tide's spring and neap shift, which could influence the coastal front and the plume extent. Typhoons happening 3–6 times in these areas over the whole summer can mix the water and decrease the hypoxic volume. Even more, the cold air southward intrusion in the summer can change the wind direction and break the hypoxia thoroughly. We hypothesize that hypoxia is not continuous in time here. How does the hypoxia break and reappear? How does it respond to tide and wind variation? What is the character of the community which can tolerate the huge environmental change? More cruises over different weather and tidal conditions are needed to answer these questions. Interdisciplinary research should be further developed in the future.

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